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# TECHNICAL MEMORANDUM

## THE ORIGIN OF LIGHT FLASHES OBSERVED BY APOLLO ASTRONAUTS

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ABSTRACT

The expected rate and intensity of Cerenkov light pulses within the eyes of Apollo astronauts, exposed to cosmic radiation away from the earth, appears too low to account for the bulk of light flashes, observed by astronauts at the rate of about one per 2 minutes, after some initial dark adaptation. Though an upper limit to the expected rate from Cerenkov radiation close to this value can be calculated, this limit would apply only if, during the periods of flash observation, the astronauts' sensitivity is at the absolute threshold of vision, and if the major part of reported light flashes are true threshold signals. Both of these related assumptions are subject to doubt. Results of laboratory exposure of human subjects to several types of particulate radiation and to energetic X-rays suggest that the bulk of reported luminous phenomena are radiation-induced phosphenes, that is, sensations of light due to direct interaction of ionizing radiation with nervous tissue in the retina. Results of experiments aboard Apollo 16 and 17 are likely to settle this issue. Until then, use of flash observations as a measure of biological hazard can have little value.

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## I. INTRODUCTION

One of the incidental phenomena reported by Apollo astronauts since the Apollo 11 mission has been their perception of light flashes during periods when the Apollo command module was darkened or when the astronauts wore eye shades (Refs. 1, 2). This phenomenon is of both intrinsic interest as an instance of sensory perception near threshold and as a potential indicator of radiation effects on nerve tissue during prolonged space flight (Ref. 2).

Analysis of the reports obtained hitherto indicate the reality of the reported phenomena as well as that their likely source was located within the astronauts' eyes and not exterior to them, a circumstance that poses the question of their physical origin. A priori, they may be due either to incidence on the retina of visible light quanta generated within the eyeball by passage of relativistic cosmic ray particles, or to direct triggering of light sensation by interaction of such nuclei or their secondaries with retinal cells or parts of the optic nerve bundle.

Observation of luminescence, produced in the vitreous humor by collisional energy loss of the passing nuclei, appears ruled out by the extremely low, if at all existent, scintillation efficiency of the waterlike vitreous humor, and by noting that such a distributed source would diffusely illuminate the entire retina, whereas the reported flashes were distinct and bright, starlike or streaklike light effects. These distinctive features also cast doubt on the recently advanced explanation of the observed flashes as being due to radiation induced scintillation of the eye lens (Ref. 33).

There can be no doubt, however, that relativistic particles moving with more than 3/4 light velocity emit Cerenkov radiation within the eyeball. Yet, apart from the copious emission of Cerenkov photons by heavy ($z \geq 6$) nuclei, Cerenkov radiation will remain undetected. The maximum of $\sim$2500-5000 photons, emitted by a particle with lesser charge in its entire passage through the eye, impinge on too large an area on the retina to provide coincidence within the area prescribed for simultaneous signal generation that leads to sensation of light. Reexamination of the Cerenkov process in view of data on vision near threshold casts serious doubt on Cerenkov radiation as the dominant cause of the reported light perception, although one estimate of the upper limit of the expected rate from this source is deceptively close to the reported rate of light flashes, which typically is about 1 per minute. The rare passage of very heavy cosmic ray nuclei, as those in the iron group, cannot be ruled out, however, from contributing a small fraction of the reported phenomena.

A circumstantial, but cogent explanation of the reported phenomenon was provided by the results of eye exposure to neutron fluxes in a range of mean kinetic energies from 3 to 300 Mev (Refs. 3-6). In all these cases, bright starlike flashes were recorded at rates that were roughly proportional to the incident fluxes. Also, sideways exposure of the head to neutron fluxes induced perception of multiple simultaneous light flashes, each with an elongated tail, which perception may be analogous to that of the light streaks reported on Apollo. Exposure to X-rays and low energy ($\sim$1 Mev) neutrons also induced perception of light, though in this case not of discrete pinpoints of light, but of diffuse illumination over the entire field-of-view. On the other hand, exposure to highly relativistic pions did not result in light perception. Since, apart from the pion experiment, in neither of the above described exposures to radiation could Cerenkov light be emitted, nor were any other kinds of visible photons produced, it appears that the reported perception of light was due to phosphenes, that is, luminous effects not produced by light. Though the actual biophysical mechanism of production of these phosphenes is yet unknown, they are likely triggered by interaction of ionizing radiation with retinal nervous tissue.

To examine the alternatives, the ALFMED (Apollo Light Flash Moving Emulsion Detector) experiment is to be included in the program of the Apollo 16 and 17 missions. In this experiment a helmet is worn whose front and side panels are multiple nuclear emulsion plates. During observing sessions the plates move with respect to each other at a given rate, while the wearer reports in real time his perception of light flashes. This enables subsequent identification of particle tracks in the emulsion that are associated with individual light flashes.

Should the ALFMED results show association of singly charged subrelativistic particles with the perception of light, its origin from Cerenkov radiation would have to be rejected. If, on the other hand, light flashes are associated only with passage through the emulsion of heavy ($z \geq 10$) relativistic nuclei, Cerenkov light would be the dominant source of the reported luminosity. This would be surprising in view of laboratory experiments on radiation-induced flash perception and in view of the sensitivity of Cerenkov light perception to the threshold of vision. Pending the ALFMED results, the favored tentative explanation is that high LET* nuclei stimulate the retinal nerve tissue directly. Without detailed knowledge, however, of the underlying biophysical mechanism, any statement on the reported light phenomenon as a measure of biological hazard lacks factual support.

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* Linear Energy Transfer

## II. EVIDENCE FOR VISUAL LIGHT PHENOMENA FROM APOLLO CREW REPORTS

While no observations of sporadic light flashes in the darkened cabin had been reported prior to Apollo 11, reports by the crews of Apollo 11 to 15 have provided increasing evidence for the physical reality of these elusive phenomena, as well as rudimentary data on some of their quantitative aspects. Heightened attentiveness of the observer is mandatory for objective description of these visual sensations that, whatever their physical cause, are close to the threshold of human perception. Thus, the absence of similar reported observations by Mercury and Gemini astronauts and by crew members on earlier Apollo missions is likely due to lack of attention, combined with unfavorable conditions of the spacecraft environment. These may include the reduced cosmic ray flux in the earth orbital missions of Mercury, Gemini and Apollo 7 and 9 and the insufficient darkening of the cabin in Apollo 8 and 10.

A detailed and generally faithful account of crew reports has been given by Turner and Ellingson (Ref. 2). A check on the primary sources of this reference demonstrated its overall accuracy and completeness. Thus, only the salient points of the available evidence, relevant to this study, will be presented here, as well as some additional statistical conclusions from the recent Apollo 14 and 15 reports, not included in Ref. 2.

1. The most strikingly consistent data on the light flashes are the limits of their reported rate. Astronauts on the five missions, Apollo 11 to 15, who observed flashes under similar conditions of rest on the couches in the darkened command module, reported an average rate of about 1 flash per 2 minutes. One observer on Apollo 14, stationed under the couches in the lower equipment bay reported significantly fewer flashes, and so did all three astronauts during one of the three scheduled observing sessions on Apollo 15; this reduction was about threefold. During these periods the sighting of light flashes was reported in real time by voice communication to mission control on earth. Statistical analysis of reports by the other two simultaneously observing Apollo 14 crew members who rested on the couches, bears out well the mean interval estimates from the earlier missions, about which no detailed records are available. Moreover, to the extent of reliance on this type of evidence, the statistical analysis of the separate and simultaneous sightings by these two

observers demonstrates convincingly the objective character of the reported light flashes. It also reveals, not too surprisingly, that the recorded observations fit the stochastic properties of a Poisson type process.

2. Of almost equal consistency is the general categorization by the astronauts of their observations into two major phenomenological types, namely spotlike flashes, and flashes displaying lateral extension. These laterally extended "streaks", as they were visually described by crew members, appeared less frequently than spotlike flashes. From Apollo 14 reports the frequency of spotlike flashes was four times higher than that of streaks. While the Apollo 12 and 13 crews stressed in their reports the exclusively horizontal direction of streaks, the crews of Apollo 14 and 15 reported streaks moving in varying directions and through different segments of the visual field. If one takes at face value the description of streaks by some astronauts as thin long lines, or as similar to cloud chamber tracks -- and

there is no reason to discount these observations -- they indicate fairly continuous, but not entirely uniform, light intensity along the streaks.

Descriptions of the more frequent spot-like flashes vary from pinpoint starlike light spots through bright central stars surrounded by a halo to flashes appearing like dim diffuse lights from behind a cloud. A substantial fraction of spot-like flashes consisted of laterally separated double stars, appearing simultaneously. Reports also mention a definite gradation in the light intensity of flashes.

3. Available evidence on the state of light adaptation is contradictory. No doubt, Apollo 11 crew members first became aware of light flashes in the darkened cabin, while closing their eyes in preparation for sleep. Once the astronauts became alert to the phenomena, however, they observed flashes also under conditions that did not conform with complete dark adaptation, which normally requires a period of about 30 minutes without

exposure to any light. The report from Apollo 12 mentions Gordon observing flashes while looking at the lit instrument panel, but quotes Conrad stating that he observed far fewer flashes than his two mates on the couches. On Apollo 14, though, the cabin was completely darkened prior to the start of the test session. To explore the effect of dark adaptation in this session, at the start of the test the three crew members shone flashlights into their eyes for a period of $\sim$10 seconds. Neither of them reported sporadic light flashes for the subsequent quarter hour or so. After that Roosa and Sheppard alike observed flashes at the customary rate, although Roosa shone a flashlight into his eyes for two additional periods of $\sim$10 seconds, at intervals of 25 and 50 minutes from start of the session. Inspection of the sequence of reported light flashes indicates that his repeated exposure to light did not affect Roosa's reported perception of light flashes, relative to the other crew members, whose dark adaptation was not interfered with after their initial exposure to flashlights. This initial light exposure, it should be noted, occurred after a long period of adaptation to light, whereas Roosa's subsequent exposures were brief. It is known (Refs. 6, 7) that the degree of dark adaptation depends strongly on duration of preceding exposure to light. Though it cannot be ruled out, it is hard to conceive that Roosa's vision returned to absolute dark threshold within the one minute that passed, on one occasion, between the time he shone his flashlight into his eyes and the instant he reported a flash event. Both Roosa's experience on Apollo 14 and Gordon's Apollo 12 observation of flashes while viewing the instrument lights, suggest that complete dark adaptation was not necessary for the perception of at least some of the reported visual phenomena, or in other words, that some of these were of an intensity possibly as much as an order of magnitude higher than absolute threshold levels. The experience of Apollo 15 is consistent with that of Apollo 14: in each of the three observing sessions flashes were first noted 10-15 minutes after the start of the experiment.

In summary of the evidence from the Apollo missions one observes that:

1. the light flashes occurred at a well attested mean rate of about one per 2 minutes, with an interval distribution fitting a Poisson distribution;
2. the flashes were of two types, spotlike or streaklike, with occasional appearance of double stars;
3. observation of the flashes required a high degree of dark adaptation, but some flashes at least are likely to have been of an intensity roughly an order of magnitude above absolute threshold;
4. the consistently reported gradation of intensity between different flashes suggests moreover that a substantial fraction of flashes were above threshold.

In view of this consistency of their reports, one has to marvel at the astronauts' acuity as observers of near threshold phenomena and at their reliability as reporters of their observations.

## III. THE HUMAN EYE AND VISION NEAR THRESHOLD

With few exceptions, the visual phenomena studied here were observed after the observers had spent some time in complete darkness. The present section reviews those aspects of the anatomy and physiology of human vision that bear on the choice between explanations for the reported near threshold phenomena.

The brief general description of the human eye that opens this review is based on several standard references (Refs. 8, 9, 10) which can be consulted for additional details. Fig. 1 shows a horizontal section of the human eye. The same types of flashes were observed by the Apollo crews with open as with closed eyes, indicating that the signals perceived were not external to the eye. This obviates a discussion here of the eye's optical system, and emphasis is placed on the eye's interior exclusive of its anterior chamber and lens.

As can be seen in the figure, the bulk of the eye's volume is taken up by the vitreous humor, a jellylike fluid that contains a network of thin protein fibers, and is highly transparent (∿90%) for visible light. The physical properties of the vitreous humor approximate those of pure water, but vary slightly with age. The ranges of these variations are (Ref. 11):

| | Young | | Old |
|---|---|---|---|
| Density | 1.0053 | → | 1.0089 |
| % $H_2O$ | 99.7 | → | 98 |
| Refractive Index | 1.3345 | → | 1.3348 |

The innermost membrane that lines the wall of the roughly spherical eyeball is the light-sensitive nervous layer of the retina, composed of paper-thin sheets of complicated structure, schematically illustrated in Figs. 2 and 3. For later reference we note that the total area of the retina is about 10 $cm^2$, discounting minor light-insensitive areas such as the blind spot, where the optic nerve emerges, and other "scotoma" at the location of blood vessels. Two basic types of photoreceptors, rods and cones, form the mosaic of the innermost layer of the retina; their relative as well as absolute areal concentrations vary in the manner illustrated in Fig. 4 (Ref. 9). Rods and cones are photochemical transducers; by light-triggered chemical transformation of the photopigment contained in their outer segments, they convert impingent visible radiation into electrical signals. These photopigments are chiefly composed of slightly modified Vitamin A, and vary in spectral sensitivity. As Fig. 4 shows, the concentration of rods greatly exceeds that of cones anywhere, except within the central area around the fovea. Cones and rods serve different functions in visual perception. Each containing one of three different pigments whose peak spectral sensitivities range from blue to red, the cones mediate daylight vision and color perception, whereas the rods serve for night vision. Since the light flashes under study are a night vision phenomenon, we shall henceforth concentrate only on the way rods operate in the process of vision, albeit some of the following considerations on the function of rods have analogs in the function of cones.

Schematically, the role of the three major components depicted in Fig. 3 can be described thus: absorption of light in the rod's photopigment,* rhodopsin, generates an electrical change; this is transmitted through the bipolar cells, serving as relays, to the ganglion cells that form the input device of the neurons, which eventually lead to the visual cortex in the brain. Microscopic observation of the retina has shown the total number of rods to be about $\sim$120 million, whereas ganglia number about one million. Though the multiple connection of several rods to a single ganglion is by no means uniform over the whole retina, on the average, $\sim$100 rods feed their signals to a single ganglion.

These neural interconnections form the physical basis of both temporal and spatial summation, which determine seeing near threshold. No visual signal will be recorded by the brain, unless a given retinal area intercepts within a given time a minimal number of photons. This number depends on the size of the area, the length of the time interval, the photon wavelength and the degree of the observer's dark adaptation. Much empirical research and theoretical speculation have been devoted to this problem over the past century, and certain conclusions emerge from perusal of recent contributions to the literature on the subject (Refs. 9, 12-20).

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* A good, concise account of the photochemical reaction involved in rod vision is given in Ref. 8.

For simplicity, the following discussion assumes monochromatic light at $\sim$510 nm, the peak of spectral sensitivity of rhodopsin. In the light of the cogent argument of Ref. 19 and its use in interpreting empirical data, it appears that the absorption of two photons within an area $a_o \sim 5 \times 10^{-5}$ cm$^2$, or impingement of ten photons on such an area, of the completely dark adapted peripheral retina has a better than even chance at evoking a neural response, provided this absorption occurs within the span of $t_o \approx .06$ sec.* This constitutes the remarkably sensitive limit of detection of the human eye. The photons' separation within the above spatial and temporal limit is not important, which explains the empirical spatial and temporal summation laws of Ricco and Bloch:

$$i_{th} \times a = C_1 \qquad a \leq a_o \qquad (3.1)$$

$$i_{th} \times t = C_2 \qquad t \leq t_o \qquad (3.2)$$

Here $i_{th}$ is threshold illumination, in photons cm$^{-2}$ sec$^{-1}$; a denotes area, t duration; $C_1$ is a constant for given duration, $C_2$ is a constant for given area. Integrating Eq. (3.1)

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* Other investigators incline towards a slightly higher minimum of photons at threshold; the statistically derived estimates vary from 2 to 5-7 (Ref. 9).

over time up to $t_o$, and an area $a \leq a_o$ thus gives the minimal number of photons evoking a neural response at threshold, as does integration of Eq. (3.2) over an area $a_o$ and duration $t \leq t_o$.

The duration $t_o$ may be connected with the time a neural stimulus is conducted to and processed by the brain. The size of unit sensitive area $a_o$ is certainly related to the synaptic connection of neural ganglia in the retina. The claim that $a_o$, the area of total summation, represents an area occupied by rods feeding into a single ganglion (Ref. 18) appears dubious in the light of experimental evidence (Refs. 15, 17). The retina has a total area of $\sim 10$ cm$^2$, contains $\sim 1.2 \times 10^8$ rods and $\sim 10^6$ ganglia; thus in the mean the area served by one ganglion is $\sim 10^{-5}$ cm$^2$, containing 100 rods. Indeed, microscopic studies of the retina have established (Ref. 13) that practically everywhere in the retina, except near the fovea, 100 rods converge to 17 bipolar cells, which in turn connect to a single ganglion. But from the evidence of Refs. 14-17, it appears that the summation area is closer to $10^{-4}$ cm$^2$, which would indicate nearest neighbors' interaction. Refs. 13, 18, and 20 also demonstrate that threshold illuminance does not show variations by orders of magnitude, as the test spot is moved over large areas of the retina. This relative constancy indicates rough uniformity of the neural switching system.

Beyond the limits of area and duration for which Ricco's and Bloch's laws hold, Bouman's interpretation of the retina and its neural system as a "coincidence scaler" (Ref. 19) appears to account well for observations of partial summation, as well as other intriguing properties of the eye, such as its amazing dynamic range of about 12 decades. In Bouman's model at least k receptor excitations by single photons must occur within "Bloch time" $t_o$ and "Ricco area" $a_o$, in order to eliminate internal noise and irrelevant quantum fluctuations of light stimuli; k depends on the eye's state of dark (or light) adaptation. On the assumption that the light stimuli follow a Poisson process, it can be shown that

$$n_{th} = n_o \ (a/a_o)^{\frac{k-1}{k}} \qquad t \leq t_o \quad a \geq a_o \tag{3.3}$$

$$n_{th} = n_o \ (t/t_o)^{\frac{k-1}{k}} \qquad a \leq a_o \quad t \geq t_o \tag{3.4}$$

$n_{th}$ is the threshold number of photons for given area a or time t, while $n_o$ is the threshold number for a Ricco area and Bloch time (Ref. 19). For k = 2, Eqs. (3.3) and (3.4) assume the form

$$n_{th}/n_o = (a/a_o)^{1/2} \qquad t \leq t_o \quad a \geq a_o \tag{3.5}$$

and

$$n_{th}/n_o = (t/t_o)^{1/2} \qquad a \leq a_o \quad t \geq t_o \qquad (3.6)$$

Eqs. (3.5) and (3.6) correspond to Piper's law of partial spatial summation and Pieron's law of partial temporal summation, thought to describe well dark adapted vision. When the background illuminance is substantially above zero, $k >> 1$, $a_o$ and $t_o$ decrease, n becomes proportional to a and to t, and summation effectively ceases.

Temporal summation is of scant interest here. The duration of cosmic ray induced light flashes is short compared to $t_o$, and they are spaced widely apart relative to $t_o$, as attested to by the evidence of Section 2. What, however, are the limits of partial spatial summation?

Fig. 5, based on data in Refs. 12, 15, 17, and 19, demonstrates the approximate validity of Piper's law for retinal test spots with angular radius up to ∿6°, that is, areas as big as ∿5 mm$^2$ which probably is as far as one needs to go in the examination of the small light spots described by the astronauts. Indeed, evidence is quoted in the literature (Refs. 15, 16) for validity of the square root relation over areas as large as ∿2 cm$^2$, which strengthens confidence in the extrapolations used below.

Fig. 6 represents the total number of 507 nm photons versus the area needed to evoke a visual signal, according to

Eq. (3.5). Four curves are included, to account for the difference in assumed minimum number, and for differences between individual observers that have been noted (e.g., Refs. 9, 16).

## IV. VISUAL PERCEPTION OF CERENKOV RADIATION GENERATED WITHIN THE EYE

While a charged particle moving with constant velocity in a vacuum does not radiate, it will do so in motion through a material medium, provided its (constant) velocity, $v = \beta c$, exceeds the phase velocity of light in the medium, $c/n$; here c denotes the vacuum velocity of light and n the index of refraction. Under these circumstances at each point of its (straight) path the moving particle emits radiation in a cone that makes an angle $\theta_c = \cos^{-1}(1/\beta n)$ with the direction of motion (see Fig. 7). Thus, in a medium with refractive index n, any particle with $\beta > 1/n$ will emit this type of radiation called Cerenkov radiation after its discoverer, P. A. Cerenkov. As was indicated in Section 3, the vitreous humor of the human eye has $n = 4/3$, and therefore any particle with $\beta > 3/4$ passing through it will emit Cerenkov radiation.

Whether the radiation actually evokes a sensation of light depends on both the concentration of photons that impinge on the retina as well as on their spectral distribution. The number of photons of energy $h\nu$ (ergs) emitted in path length dl (cm) by a particle of charge Z and given $\beta$ is

$$\frac{dN}{dl} = 2\pi\alpha Z^2 \; (1-1/\beta^2 n^2) \; d\nu/c \text{ photons cm}^{-1} \text{ Hz}^{-1} \tag{4.1}$$

where $\alpha = e^2/(hc) = 1/137$ is the fine structure constant, and Z the nuclear charge of the moving particle. In the range of interest the refractive index n of the vitreous humor is virtually independent of frequency, so that the frequency spectrum of Cerenkov radiation generated within the eye is flat. But the retinal sensitivity to light depends on frequency, and in particular the scotopic sensitivity, that is, the sensitivity of rods, varies with wavelength in the fashion illustrated in Fig. 8: photons at different wavelengths are not equally effective in producing visual perception. We shall, therefore, define an effective number of photons, $N'(\lambda)\, d\lambda$, given by the product of $N(\lambda)\, d\lambda$, the number of photons emitted at a wavelength $\lambda$, and of a weighting function $W(\lambda)$, represented by the dashed trapezoid in Fig. 8, and normalized to unity at $\lambda = 500$ nm, near the peak of scotopic sensitivity of the human retina. $W(\lambda)$ can be represented as

$$W(\lambda) = \begin{cases} 0 & \lambda \leq 400 \text{ nm} \\ -4 + \lambda/100 & 400 \text{ nm} \leq \lambda \leq 500 \text{ nm} \\ 1 & 500 \text{ nm} \leq \lambda \leq 515 \text{ nm} \\ (585-\lambda)/70 & 515 \text{ nm} \leq \lambda \leq 585 \text{ nm} \\ 0 & 585 \text{ nm} \leq \lambda \end{cases} \tag{4.2}$$

Conversion of Eq. (4.1) to wavelength yields

$$\frac{dN}{dl} = 2\pi\alpha Z^2 \sin^2 \theta_c \, d\lambda/\lambda^2 \text{ photons cm}^{-2}$$

$$= 2 \times 10^7 \, \pi\alpha Z^2 \sin^2 \theta_c \, d\lambda/\lambda^2 \text{ photons cm}^{-1} \text{ nm}^{-1} \qquad (4.3)$$

Integrating $W(\lambda)$ $dN/dl$ over $\lambda$ we obtain for the total effective number of visible photons emitted in 1 cm path length by Cerenkov radiation

$$\frac{dN'}{dl} \approx 188 \, Z^2 \left(1 - \frac{9}{16 \, \beta^2}\right) \text{ photons cm}^{-1} \qquad (4.4)$$

Thus the number of effective Cerenkov photons emitted per unit path length is proportional to the square of nuclear charge Z, and for $n = 4/3$, goes from 0 at $\beta = 3/4$ to a maximum of $\sim$82 at $\beta = 1$. Whether these photons will be perceived therefore depends on both the charge Z, and the relative velocity $\beta$, as well as on the path length traversed by the particle within the eye. The rate of Cerenkov light perception by a dark adapted human observer exposed to cosmic radiation, will then be given by the rate of cosmic ray nuclei that impinge on the observer's eye and satisfy the conditions of perceptibility derived below.

Path length within the eye is obviously not an intrinsic property of the particles; path lengths depend on the particle's angle of incidence on the eye and are statistically distributed. The rate of perceived Cerenkov light flashes is certainly proportional to cosmic ray intensity. It is, therefore, advantageous to eliminate path length from consideration in developing a criterion of perceptibility for Cerenkov light emitted by relativistic cosmic ray particles within the eye. This can be accomplished with relative ease because of the simple geometry of Cerenkov radiation and the simple form of Piper's law, expressed by Eq. (3.5). Eq. (A.6) in Appendix A provides this required criterion in the form of a relation between the particles charge Z and its velocity $\beta$.

$$Z \geq 1.724 \, M^{1/2} \quad [(16 \, \beta^2/9)-1]^{-1/4} \qquad (4.5)$$

Due to its parametric dependence on M, the minimal number of photons incident on a Ricco area, this relation also takes into account a sufficient range in individual observers' states of dark adaptation.

Fig. 9 presents a map of the $\beta$, Z plane, where lines of equal perceptibility, labeled by their respective M values, divide this plane into "perceptible" areas, above and to the right of these lines, and "imperceptible" areas comprising the remainder of the plane. Particles with charges and velocities in the "perceptible" area that emit Cerenkov radiation within the eye, should evoke a visual signal, almost independent of their path length within the eye; those with charge and velocity outside those areas generate too weak a signal to be perceived.* What immediately stands out from Fig. 9 is that singly and doubly charged nuclei, such as protons and alpha particles that make up the bulk of cosmic radiation, as well as electrons, can never be perceived by means of their Cerenkov radiation within the eye. Clearly the results embodied in Fig. 9 indicate also that the light sensations statistically associated with cosmic ray muons that were reported some years ago (Ref. 21), could not have been engendered by Cerenkov light, muons being singly charged.

In the absence of empirical evidence it would be premature to predict the character of the visual sensation produced by Cerenkov light internal to the eye. Since in most cases the signal is just above threshold, it can be expected that the sensation will be rather like that of a pinpoint source of light rather than of a diffuse disc. The latter probably occurs only in the rare cases when a heavy and fast nucleus emits a quantity of Cerenkov photons that is profuse by the yardstick of Eq. (4.5).

## V. PERCEPTION OF CERENKOV LIGHT FLASHES DURING APOLLO MISSIONS

The criterion of perceptibility, Eq. (4.5), provides a convenient basis for estimates of the expected rate of Cerenkov light perception in Apollo missions; these estimates

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* For convenience of presentation, the discrete nature of charge values Z was disregarded in Fig. 9.

vary, however, with the assumed threshold number M. The expected rate obviously equals the rate of incidence on the astronauts-observers' eyes of cosmic ray nuclei that satisfy the criterion of Eq. (4.5). Table 1 shows these rates in their dependence on M.

The table is based on the rigidity spectra of heavy cosmic ray nuclei in Refs. 22 and 23, which represent observations in the 1966 epoch, whereas the Apollo 14 mission took place in early February 1971. While the intensity of galactic cosmic rays is affected by solar activity, its levels in the two indicated periods were similar, and even if differences are taken into account, the modulation of the high rigidity portion of the spectrum involved should not exceed about 20% (Refs. 24-26). Consequently, as far as cosmic ray variations are concerned, Table 1 should present reliable values.

As one looks at Table 1 he is struck by the fact that the numbers appearing in the table bracket so nicely the frequency of light flashes observed in past mission, which is likely the reason Cerenkov radiation has been favored as the explanation of light flashes by several investigators (Refs. 27-28). But a harder look at the meaning of the results in Table 1 should convince us that caution is advised in the interpretation of this probably fortuitous coincidence.

In particular, the factors determining threshold photon numbers M are in need of scrutiny, since they regulate

TABLE 1

Cutoff Rigidities $R_c$ (GV) and Mean Interval $\tau$ (sec) Between Cerenkov Light Flashes in Various Cosmic Ray Charge Groups as a Function of Photon Threshold Number M *

| M / z | 10 | | 30 | | 50 | | 100 | | 150 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $R_c$ | $\tau$ | $R_c$ | $\tau$ | $R_c$ | $\tau$ | $R_c$ | $\tau$ | $R_c$ | $\tau$ |
| 6-9 | 3.2 | 40 | - | - | - | - | - | - | - | - |
| 10-14 | 2.16 | 125 | 2.67 | 135 | 3.16 | 170 | - | - | - | - |
| 20 | 2.30 | 300 | 2.30 | 300 | 2.30 | 300 | 2.5 | 330 | 2.9 | 400 |
| Total | | 30 | | 95 | | 105 | | 330 | | 400 |

* The values of $R_c$ in the table constitute an appropriate average over the admissible members of the group. The values of $\tau$ are rounded off to the nearest multiple of 5. Where no entry appears, the particular charge group does not contribute perceptible Cerenkov light.

the fit of observation to computed results. Apart from the controversy about the absolute minimum of 2 or 5-7 absorbed photons for visual perception (see Section 2), and apart from the clear differences between individual observers, easily amounting to a factor of 5 (see, e.g., p. 167 in Ref. 18), the crucial factor is background illumination, internal or external to the eye.

Internal background illumination, which would be the sole disturbance when eyeshades are worn, appears to be insignificant. It would have to be produced by the scintillation of the vitreous humor upon passage through it of cosmic ray particles and/or their particulate or radiative secondaries. The scintillation properties of water are still subject to controversy (Refs. 29, 30). However, even if we accept the high estimate of $\sim$1.5 visible photons per $cm^3$ per second at the earth's surface (Ref. 29), where about $2 \times 10^{-2}$ muons are incident on 1 $cm^2$ per second, and extrapolate to the hundredfold flux of cosmic ray nuclei in space (Ref. 31), we get about $10^3$ photons per second per eye, or about 50 photons per incident cosmic ray particle. Obviously, distinct from Cerenkov photons, photons from this source would diffuse over the entire retina, and therefore fall far short of detectability, without affecting background illumination.

On the other hand, from the reports summarized in Section 2, the simultaneous exposure of one astronaut to the light of the instrument panel and the intermittent exposure to flashlight of another should have measurably affected their threshold. In absence of quantitative data on the luminance of the instrument panel, we will not estimate the degradation of dark adaption due to this exposure. But shining a flashlight into his eyes for 10 seconds must have raised astronaut Roosa's threshold by at least a factor of 3-5 (Ref. 18) at the instant he reported flashes subsequent to his exposures.

This, together with the previously noted factor of 5 associated with individual differences, suggests that the higher M values of Table 1, 100-150, probably conform more to reality, so that perception of Cerenkov light is no longer a tenable explanation for the majority of light flashes. Impact of iron group nuclei that is required at high M values, occurs too infrequently to account for the observed rate. But, in view of their high charge and, consequently, profuse photon emission, the heavy nuclei may well be the cause of the occasionally reported dim, halolike light spots.

In addition to the grave doubts raised on the Cerenkov light hypothesis by considering the threshold levels and associated expected frequency of events, the observed morphology of part of the phenomena speaks against this hypothesis; there is no way to reconcile the generation of light streaks with this mechanism.

In summary, then, it appears that only by stretching estimates very far can coincidence with observations be maintained, so that an alternative explanation for the bulk of observed phenomena is called for.

## VI. THE ALTERNATIVE, DIRECT INTERACTION; CONCLUSIONS

Pending the outcome of the ALFMED experiment on Apollo 16 and 17, which hopefully will settle the matter, the most plausible explanation of the observed light flashes is the triggering of light sensation by direct energy transfer from cosmic ray particles to optical receptors and/or associated nerve fibers. If this is indeed the case, the reported sensations are phosphenes induced by particulate radiation, and are not due to actual perception of light.

The probability of this explanation has been recently demonstrated in convincing manner by a series of experiments aimed at resolution of the problem (Refs. 3-5). Since these references provide detailed descriptions of the experiments, we shall here only summarize the salient facts bearing on the issue.

a. 70 sec exposure of a dark-adapted subject to a flux of $10^4$ $Cf^{252}$ fission neutrons $cm^{-2}$ $sec^{-1}$ resulted in perception of a single bright flash; 12 sec exposure to a flux of $10^4$ neutrons $cm^{-2}$ $sec^{-1}$ led to perception of slight haze. $Cf^{252}$ fission neutrons span an energy range from 0-$\sim$12 Mev, with a spectrum that peaks sharply at 1 Mev.

b. Exposures for $\sim$100 sec to a flux of $10^5$ neutrons $cm^{-2}$ $sec^{-1}$ from deuteron bombardment of a beryllium target, induced perception of multiple (tens to hundreds) simultaneous starlike flashes against a slightly hazy background. Upon lateral exposure, streaklike flashes were perceived. Even when the flux was reduced by 1-2 orders of magnitude, light flashes were perceived by one subject. The $Be^9(d,n)B^{10}$ reaction yields a broad spectrum between and 20 Mev, peaked at $\sim$8 Mev. Some gradation of brightness was also observed.

c. Short (3-4) sec exposures to fluxes of $10^4$ neutrons sec $cm^{-2}$ from a beryllium target bombarded by .64 GeV protons produced sensation of bright starlike flashes at a rate of 25-50 flashes $sec^{-1}$. These neutrons have an energy spectrum peaked at $\sim$300 Mev, and consequently the fraction of recoil protons produced in the eye with $\beta \geq 3/4$ is minute. Lateral exposure produced sensation of stars with elongated tails. The total dose in these exposures was $\sim$.5 mR at a rate of $\sim$.1 mR/sec.

d. Exposure of each eye to $\sim$5000 1.5 GeV/c momentum pions ($\beta$>.995) did not produce any light sensation.

e. Exposure to 250 kv X-rays at dose rates of less than 1.25 mR $sec^{-1}$ produced no light sensation; dose rates of 1.25 mR or higher produced sensation of soft diffuse light spread over the entire visual field of both eyes.

This list can be complemented by an additional instance of light perception upon exposure to a 3 MeV neutron beam of $10^5$ neutrons $cm^{-2}$ $sec^{-1}$, a rate of 10-20 flashes per second was reported (Ref. 32). Furthermore, in all reported experiments as well as in earlier X-ray experiments, a definite directional effect was observed that points to a near retinal location of whatever interaction produced the sensation of light. A recent experiment also demonstrates clearly that the visual cortex cannot be considered the site of interaction (Ref. 34).

The above facts lead in a straightforward manner to the following conclusions.

a. Discrete light flashes can be produced by non-relativistic nuclei of relatively low energy. Light flash perception was induced by the low energy charged recoil nuclei produced by the neutrons from the $Be^9(d,n)\ B^{10}$ reaction.

b. There appears to be an energy threshold for the production of discrete light flashes by particles, the threshold for neutrons lying between 1 and 3 Mev.

c. Perception of diffuse light is induced both by exposure to high fluxes of lower energy (1 Mev) neutron fluxes as well as to high fluxes of 250 kV X-rays.

d. Exposure to singly charged relativistic particles does not result in the perception of light flashes.

e. There appears to be gradation of the perceived light intensity.

f. The actual physical mechanism of phosphene induction by either kind of radiation is as yet unknown.

For the purposes of this study, conclusion a. appears most significant: the very perception, on exposure to Mev range nuclei, of starlike flashes similar to those "seen" by the Apollo astronauts suggests the validity of the conclusions drawn in Refs. 3-5, namely, that the reported phenomena result from non-photic neural stimulation. This is reinforced by the negative conclusions of Section 5 about Cerenkov radiation as a light source: interaction of incident cosmic ray particles with the retinal tissue, without intermediate emission of light is the likely origin of the reported phenomena. Should, indeed, the results of the ALFMED experiment demonstrate incidence on the astronaut's eyes of sub-relativistic particles simultaneously with the perception of light flashes, the matter will be settled.

Yet, a major fraction of the cosmic ray particles are relativistic with $\beta > 3/4$ -- 80% of protons and >50% of heavier nuclei -- and the production of phosphenes may appear to coincide with impact of relativistic particles. In this case, the results of Section 4 show that the coincidence of proton or alpha particle impact with light perception would eliminate Cerenkov radiation as causative agent.

It would be presumptuous to indulge here in discussing the actual mechanism that induces light perception. Nonetheless, the production of phosphenes by both particles and .25 Mev X-rays suggests that the secondary electrons produced in the traversal of radiation through the retinal tissue must play the decisive role in the energy transfer that produces a light signal. Investigation of the secondary electron spectra produced by the various radiations employed in the experiments and of their differences should provide a clue to the required mechanism. The fact, however, that an energy threshold appears to exist for the production of phosphenes (b. above) suggests that high $LET_\infty$ by itself is not sufficient.

This would be consistent with the assumption that energy transfers of many hundreds of eV in a single cell are involved (Ref. 2).

A final word about the hazards to retinal tissue signalled by the perception of light flashes is in order: the very rarity of the reported phenomena, compared to the total expected rate of cosmic ray impacts on the eye, and the present uncertainty in their correlation with the cosmic ray spectrum reduce the value of light flash perception as an indicator of harmful radiation dosage. Not until the biophysical mechanism is better understood can valid predictions of damage to the retina be based on the reported rate of light flashes.

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Attachments

## APPENDIX A

## DERIVATION OF A CRITERION OF PERCEPTIBILITY FOR CERENKOV LIGHT EMITTED BY ENERGETIC PARTICLES WITHIN THE HUMAN EYE

Fig. A1 shows that all 188 $Z^2 \sin^2\theta_c$ 1 effective photons emitted by a cosmic ray particle in a path length 1 through the vitreous humor impinge on a circular patch on the retina of area

$$a = \pi l^2 \tan^2 \theta_c \qquad \text{(A.1)}$$

Here the curvature of the eye is neglected and normal impact of the particle on the eye is assumed. Neglect of curvature results in a maximal overestimate of illuminated retinal area by less that 15%, which occurs when a particle with $\beta = 1$ traverses the eye diametrically. But cosmic ray intensity in all charge ranges decreases sharply with increasing $\beta$, and the bulk of particles emitting Cerenkov radiation will do so in a very narrow cone -- $\theta_c = 0$ for the lower limit $\beta = 3/4$ -- and the illuminated retinal area will be practically flat. Now, Eq. (A.2) gives the ratio of the circular area $a_c$ that results from normal intersection of a plane with a cone of half angle $\theta_c$ whose vertex is at a height 1 above the plane to the elliptic area $a_e$ of intersection that results when the same cone is inclined to the plane at an angle $\alpha$ and its vertex at a higher $l \sin \alpha$:

$$\frac{a_c}{a_e} = \frac{[\cos(\theta_c+\alpha)\ \cos(\theta_c-\alpha)]^{3/2}}{\cos^3 \theta_c \cos^2 \alpha} \tag{A.2}$$

$$\rightarrow \cos \alpha \qquad \text{for } \theta_c \rightarrow 0$$

Thus, for oblique incidence of a narrow cone of light, the number of photons per unit area varies as $\cos \alpha$, where $\alpha$ is the angle between the emitting particle's path and the radius vector in the eye to the point of the particle's exit from the eyeball (Fig. A.2). Cosmic radiation is isotropic, so that the average of $\cos \alpha$ over the hemisphere of allowed angles $\alpha$ is given by $1/\pi$. Then, on the average, the elliptic area of the intersection is increased by a factor $\pi$. We assume, therefore, that on the average a cosmic ray particle emitting Cerenkov light in a path length $l$ illuminates an area

$$a = \pi^2\ l^2\ \tan^2 \theta_c \tag{A.3}$$

In deriving this average we neglected the correlation between path length $l$ and angle of incidence $\alpha$ that is a consequence of the eye's roughly spherical shape. This neglect leads a priori to a slightly more conservative criterion, which is desirable, as it compensates for other factors of comparable magnitude that are neglected, such as the weak absorption of light by the vitreous humor itself. In view of greater uncertainties, such as in the threshold values for light perception, the neglect of those minor effects appears insignificant.

From Eqs. (4.3) and (4.4) we find the number of photons emitted in path length l

$$N = 188 \sin^2 \theta_c Z^2 l \tag{A.4}$$

Letting M be the minimal number of photons incident on a Ricco area $a_o$, we obtain from Piper's law, Eq. (3.5), the required minimal number of photons per unit area

$$\rho \geq (a\, a_o)^{-1/2} M \tag{A.5}$$

Using Eqs. (A.3) and (A.4) in the expressions for a and $\rho$, and recalling that $a_o \approx 10^{-4}$ cm$^2$, we thus obtain as the criterion of perceptibility in the desired form, independent of path length

$$Z \geq 1.724\, M^{1/2}\, \beta/(16\beta^2/9-1)^{1/4} \tag{A.6}$$

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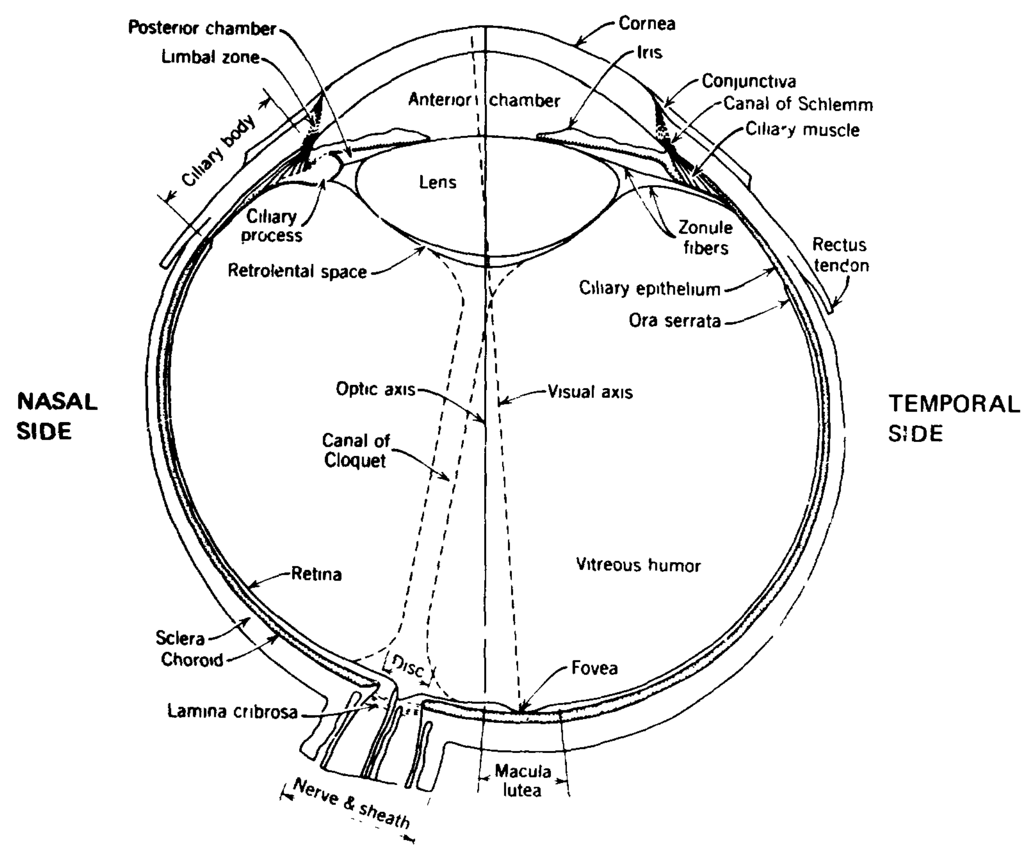


FIGURE 1 - HORIZONTAL SECTION THROUGH RIGHT HUMAN EYE

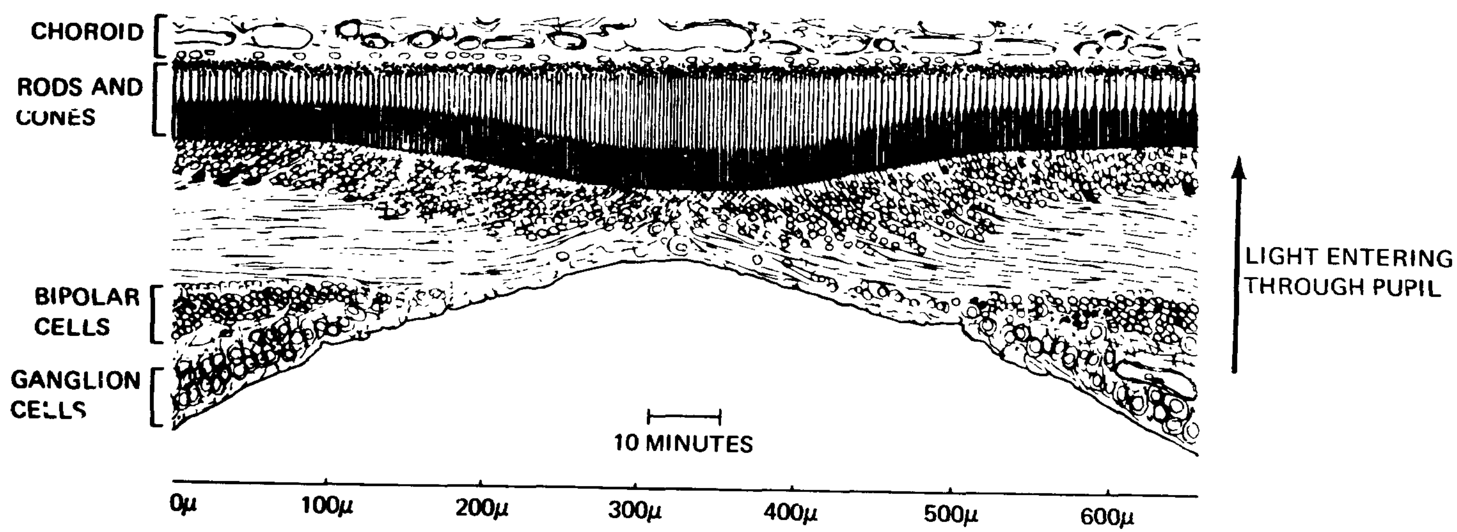


FIGURE 2 - CENTRAL FOVEA OF THE HUMAN RETINA

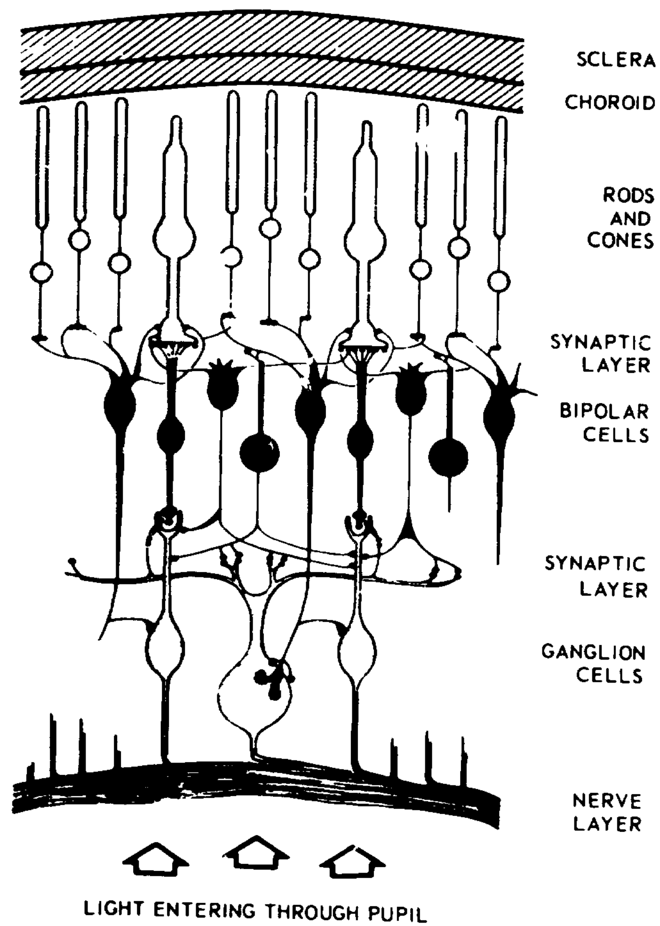


**FIGURE 3 - ORGANIZATION OF THE RETINA (SCHEMATIC)**

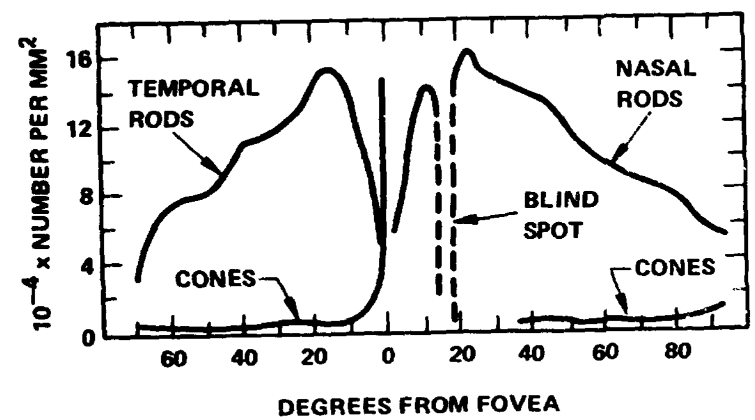


FIGURE 4 - DISTRIBUTION OF RODS AND CONES IN THE HUMAN RETINA (REF. 9)

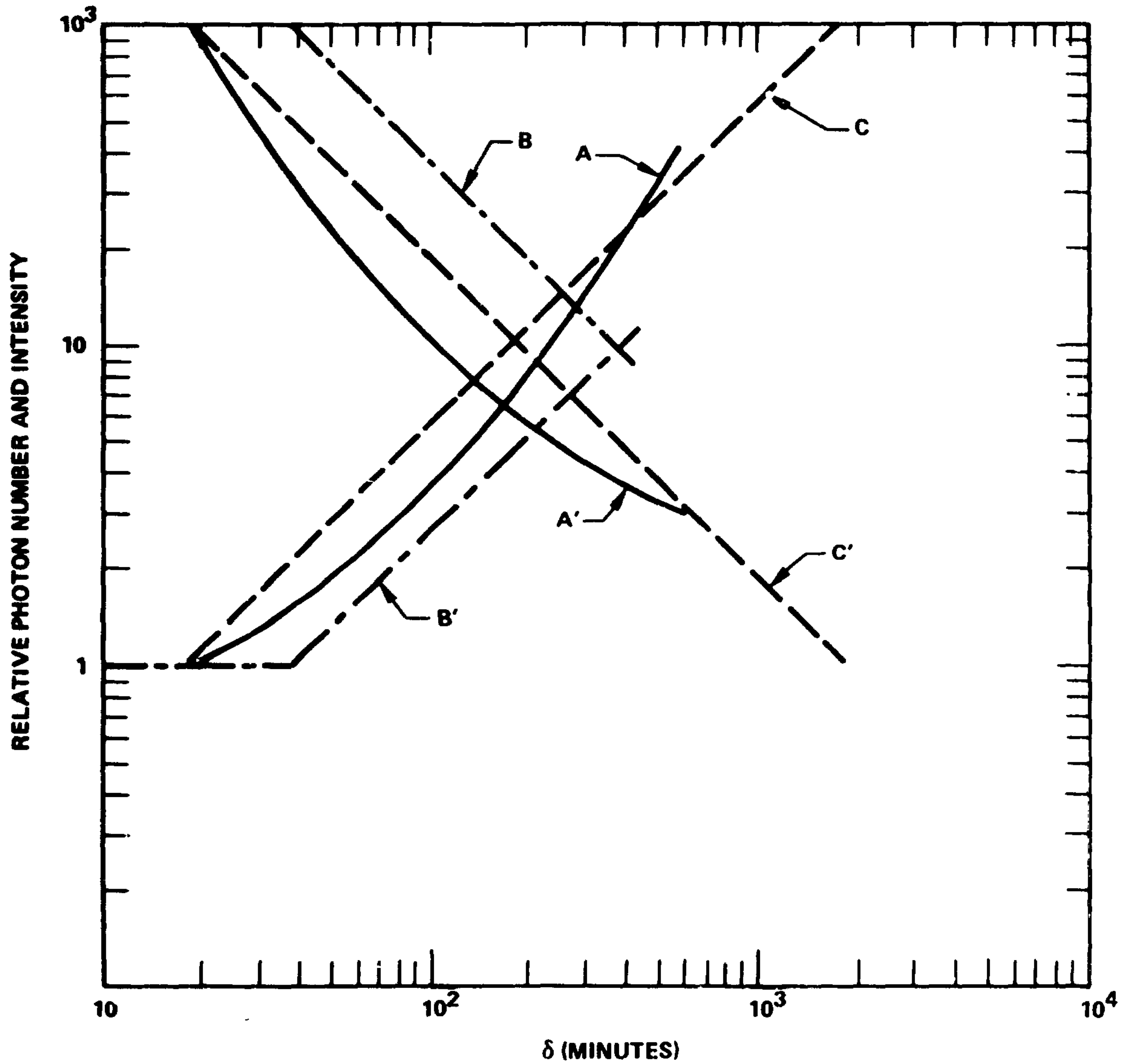


FIGURE 5 - RELATIVE NUMBER OF PHOTONS (UNPRIMED CURVES) AND INTENSITY (PRIMED CURVES) VERSUS ANGLE OF VISION δ (MINUTES); CURVES A & A' FROM REF. 12, B & B' - REF. 15, C & C' - REF. 17

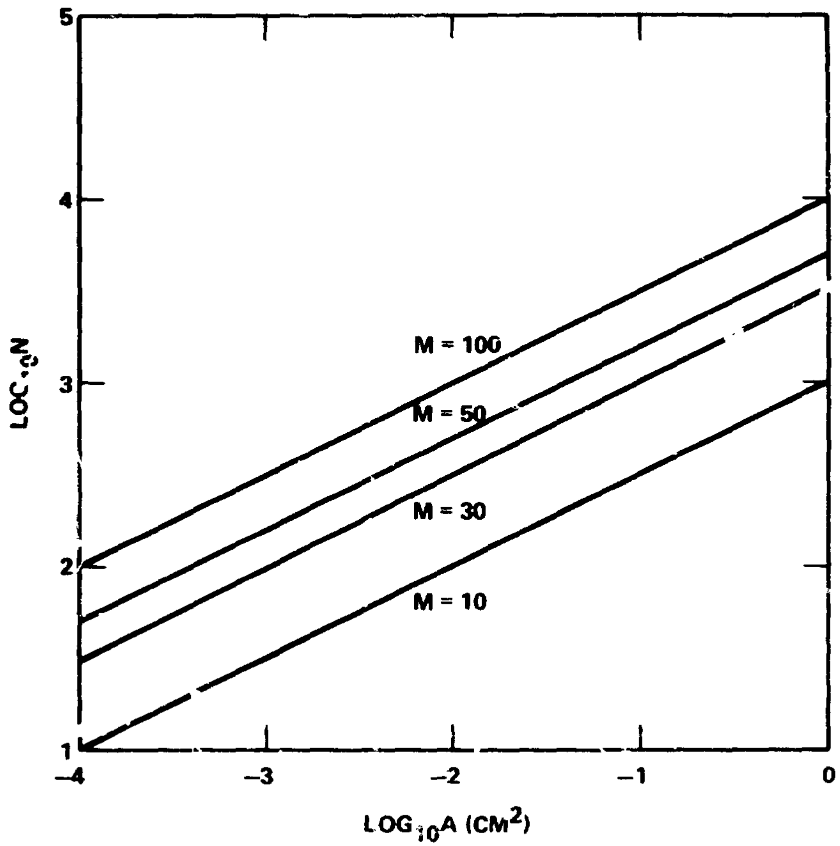


FIGURE 6 - NUMBER OF PHOTONS VERSUS AREA A ($CM^2$)
AS A FUNCTION OF THRESHOLD NUMBER M

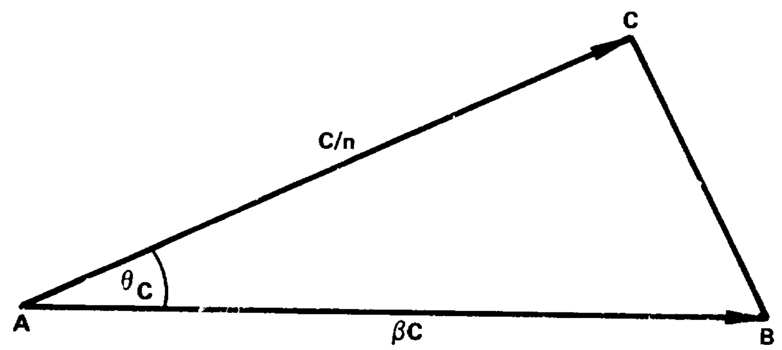


FIGURE 7 - EMISSION OF CERENKOV RADIATION BY A CHARGE MOVING WITH VELOCITY $\beta c$ THROUGH MEDIUM WITH REFRACTIVE INDEX n. $\theta_C = \cos^{-1} (1/\beta_n)$ IS ANGLE OF EMISSION

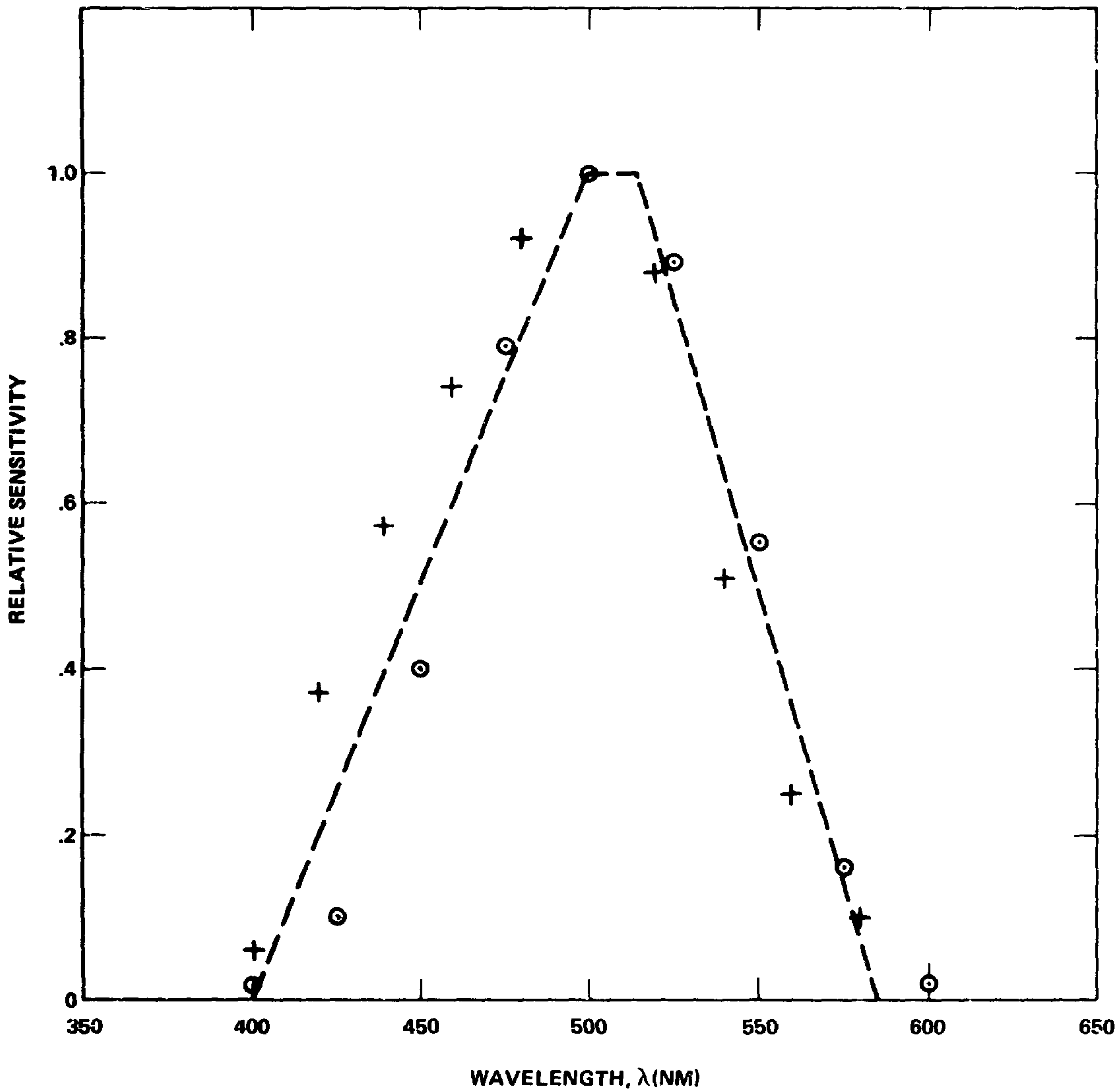


FIGURE 8 - WAVELENGTH DEPENDENCE OF SCOTOPIC SENSITIVITY;
EXPERIMENTAL DATA - O, + FROM REFS. 8, 9;
— — — APPROXIMATION USED IN TEXT

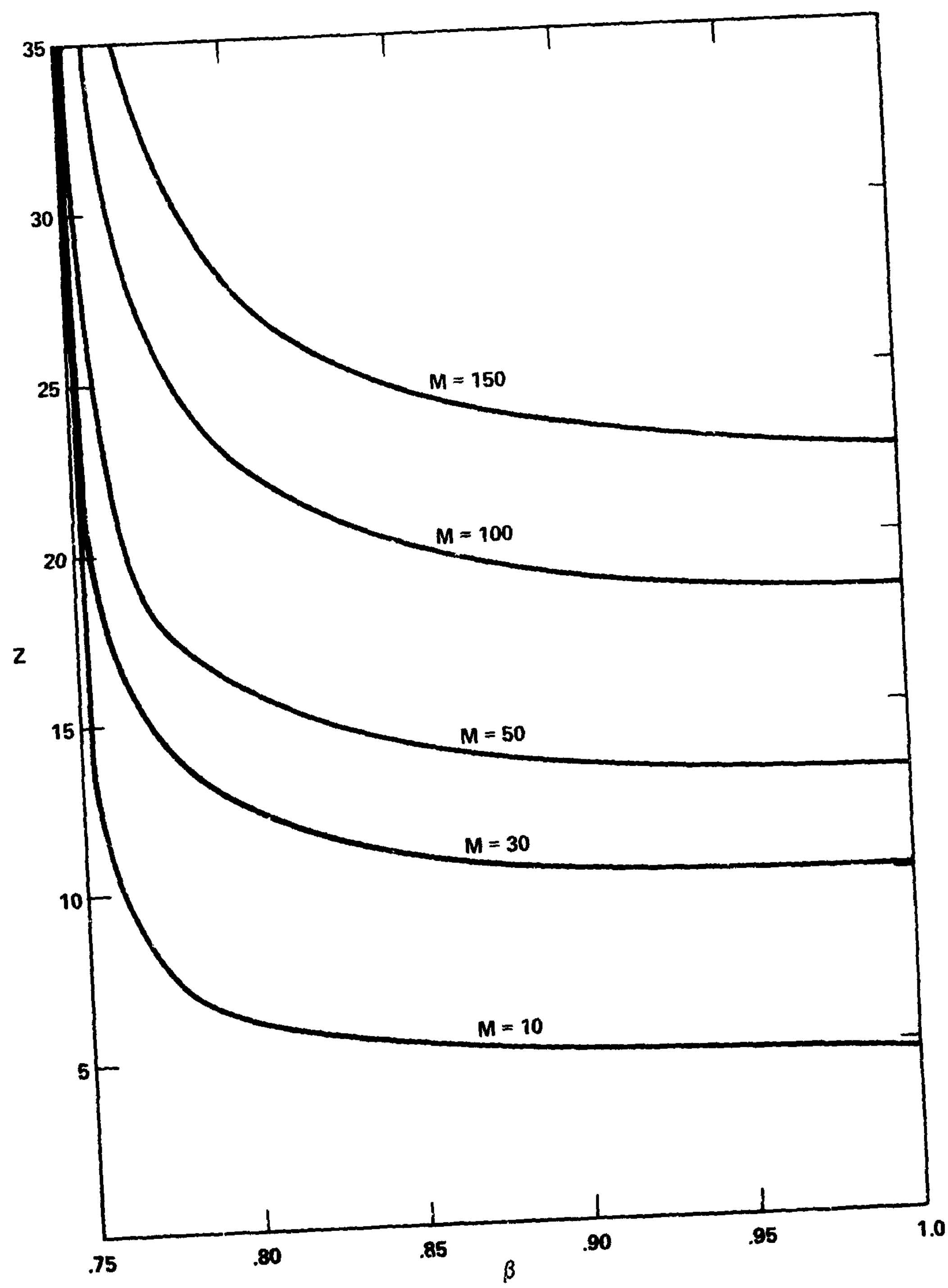


FIGURE 9 - CONTOURS OF EQUAL PERCEPTIBILITY OF CERENKOV LIGHT, EMITTED IN THE EYE BY PARTICLES OF CHARGE Z AND VELOCITY V = $\beta$C, AS A FUNCTION OF THE THRESHOLD NUMBER OF PHOTONS M

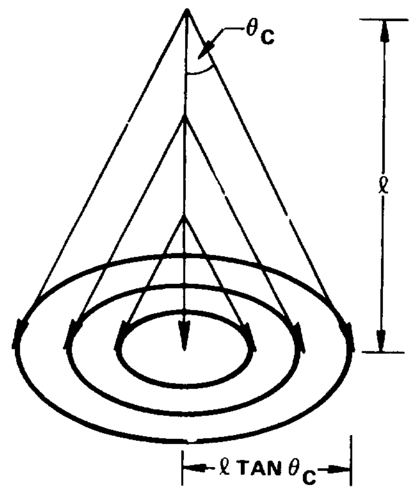


FIGURE A1 - ILLUMINATION OF CIRCULAR AREA $\pi\ell^2 TAN^2\theta_C$ BY CERENKOV LIGHT EMITTED IN PATHLENGTH $\ell$ BY NORMALLY INCIDENT CHARGE

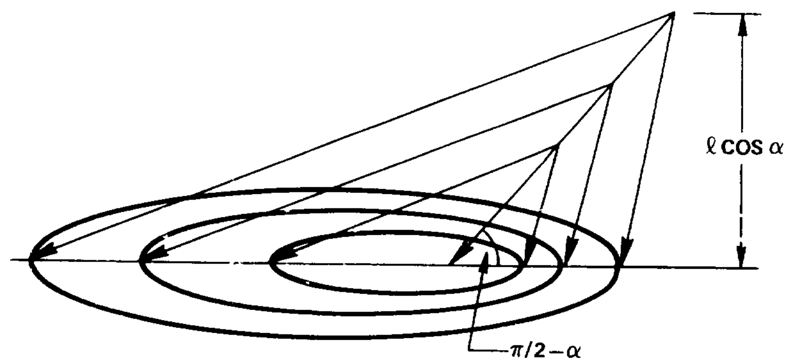


FIGURE A2 - ILLUMINATION OF ELLIPTIC AREA BY CHARGE INCIDENT AT ANGLE $(\pi/2-\alpha)$